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## Time since death and decay rate constants of Norway spruce and European larch deadwood in subalpine forests determined using dendrochronology and radiocarbon dating

Petrillo, Marta ; Cherubini, Paolo ; Fravolini, Giulia ; Marchetti, Marco ; Ascher-Jenull, Judith ; Schärer, Michael ; Synal, Hans-Arno ; Bertoldi, Daniela ; Camin, Federica ; Larcher, Roberto ; Egli, Markus

**Abstract:** Due to the large size (e.g. sections of tree trunks) and highly heterogeneous spatial distribution of deadwood, the timescales involved in the coarse woody debris (CWD) decay of *Picea abies* (L.) Karst. and *Larix decidua* Mill. in Alpine forests are largely unknown. We investigated the CWD decay dynamics in an Alpine valley in Italy using the chronosequence approach and the five-decay class system that is based on a macromorphological assessment. For the decay classes 1–3, most of the dendrochronological samples were cross-dated to assess the time that had elapsed since tree death, but for decay classes 4 and 5 (poorly preserved tree rings) radiocarbon dating was used. In addition, density, cellulose, and lignin data were measured for the dated CWD. The decay rate constants for spruce and larch were estimated on the basis of the density loss using a single negative exponential model, a regression approach, and the stage-based matrix model. In the decay classes 1–3, the ages of the CWD were similar and varied between 1 and 54 years for spruce and 3 and 40 years for larch, with no significant differences between the classes; classes 1–3 are therefore not indicative of deadwood age. This seems to be due to a time lag between the death of a standing tree and its contact with the soil. We found distinct tree-species-specific differences in decay classes 4 and 5, with larch CWD reaching an average age of 210 years in class 5 and spruce only 77 years. The mean CWD rate constants were estimated to be in the range 0.018 to 0.022 y<sup>-1</sup> for spruce and to about 0.012 y<sup>-1</sup> for larch. Snapshot sampling (chronosequences) may overestimate the age and mean residence time of CWD. No sampling bias was, however, detectable using the stage-based matrix model. Cellulose and lignin time trends could be derived on the basis of the ages of the CWD. The half-lives for cellulose were 21 years for spruce and 50 years for larch. The half-life of lignin is considerably higher and may be more than 100 years in larch CWD. Consequently, the decay of *Picea abies* and *Larix decidua* is very low. Several uncertainties, however, remain: <sup>14</sup>C dating of CWD from decay classes 4 and 5 and having a pre-bomb age is often difficult (large age range due to methodological constraints) and fall rates of both European larch and Norway spruce are missing.

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1    **Time since death and decay rate constants of Norway spruce and European**  
2    **larch deadwood in subalpine forests determined using dendrochronology and**  
3    **radiocarbon dating**

4  
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## 25    **Abstract**

26    Due to the large size (e.g. sections of tree trunks) and highly heterogeneous spatial distribution of  
27    deadwood, the time scales involved in the coarse woody debris (CWD) decay of *Picea abies* (L.)  
28    Karst. and *Larix decidua* Mill. in Alpine forests are largely unknown. We investigated the CWD  
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40    and 5, with larch CWD reaching an average age of 210 years in class 5 and spruce only 77 years.  
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to methodological constraints) and fall rates of both, European larch and Norway spruce are missing.

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Keywords: coarse woody debris, decay constants, Norway spruce, European larch, subalpine forests, cellulose, lignin

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## 56 **1 Introduction**

The quantity and residence time of deadwood or coarse woody debris in Alpine forests are crucial in assessing the carbon cycle to ensure sustainable management of forests. Coarse woody debris (CWD) is defined as large-sized deadwood pieces, such as stems of dead trees lying on the forest floor, standing dead trees and stumps, big branches and wood boles in all stages of decomposition. Deadwood plays an important role in maintaining biodiversity in forest ecosystems (Müller and Bütler, 2010) as well as storing carbon (Di Cosmo et al., 2013), and contributing to nutrient cycle processes (Palviainen et al., 2010). The amount of deadwood varies greatly from managed to natural forests. In managed European Alpine forests, for example, the average stock of deadwood is estimated to be about  $26 \text{ m}^3 \text{ ha}^{-1}$ , while in old growth Alpine coniferous forests it can be up to  $150 - 190 \text{ m}^3 \text{ ha}^{-1}$  (Barbati et al., 2014). Residence time for deadwood (e.g. Krüger et al., 2014) — from the moment the tree reaches the forest floor until it loses 95 % of the mass — can range from decades to several hundred years, depending on intrinsic and external factors. These factors include the dimensions of the log, the wood chemistry and the site conditions, in particular the mean annual temperature and soil moisture.

Until now, various different sampling designs have been used to determine the time since death to estimate the decay rate of deadwood. Long-term studies can provide reliable results (Müller-Using and Bartsch, 2009), but the slow decay dynamics of wood usually require a decadal observation

74 period. Bond-Lamberty and Gower (2008) used the ratio of deadwood mass input into the pool of  
 75 initial deadwood to estimate its decay rate based on a 7-years observation period. Such time  
 76 sequences (chronosequence) offer ideal scenarios to study deadwood dynamics. If windthrow, fire  
 77 regeneration and harvest events are known, the starting point in the timeline of the decay process  
 78 can be specified. However, the exact year of such events is often uncertain which means precisely  
 79 dating a tree's death is critical. Dendrochronology can be a helpful tool to determine the year of  
 80 death, and the technique has been used in several studies to determine the time elapsed since tree-  
 81 death (Campbell and Laroque, 2007, Lombardi et al., 2008, 2013). Other researchers have used  
 82 radiocarbon dating to date the last recognizable ring of deadwood. For example, Kueppers et al.  
 83 (2004) estimated the turnover time of lodgepole pine along a subalpine elevation gradient and  
 84 Krüger et al. (2014) compared tree-ring cross-dating and radiocarbon dating, demonstrating that the  
 85 two techniques produce comparable results. The decay rate can be estimated by relating the time-  
 86 since-death to the density loss or mass loss of deadwood during a given time period (e.g. Busse,  
 87 1994; Melin et al., 2009). The decay rate is commonly expressed through a decay constant  $k$ , which  
 88 indicates the density loss or mass loss per year. This constant is derived from a decay model  
 89 (Harmon, 1986), which can be most simply expressed by the equation

$$x_t = x_0 e^{-kt} \quad (1)$$

91 (single-negative-exponential model), where  $x_t$  is the density or mass of deadwood at a given time,  
 92 and  $x_0$  is the initial density or mass (Jenny et al., 1949; Olson, 1963). Other decay models have also  
 93 been developed that take wood decomposition into account (reviewed by Mackensen et al., 2003).  
 94 Several authors (Minderman, 1968; Wider and Lang, 1982; Means et al., 1985) consider the  
 95 different wood components, e.g. bark, sapwood, heartwood and chemical compounds, and combine  
 96 them in multiple-exponential equations. Other authors (e.g., Harmon et al., 1986) consider the time  
 97 elapsed from the death of a standing tree to the moment when it falls and comes in contact with the  
 98 forest floor (lag-time models). In several environments, e.g. on dry mountain slopes, the time lag  
 99 between death and contact with the forest floor can last for almost the entire decay process

100 (Kueppers et al., 2004). A few models take not only the losses due to heterotrophic respiration and  
101 leaching into account, but also losses due to fragmentation (Mackensen et al., 2003).

102 One of the most important components of deadwood is coarse woody debris. Because the spatial  
103 distribution of CWD is highly heterogeneous, only little quantitative data about its long-term decay  
104 dynamics are available for European Alpine forests. Decay models in Europe have, therefore, rarely  
105 been parameterised using empirically derived decay constants. In the field, the different stages of  
106 CWD decomposition are often described by so-called decay classes (as defined by Hunter, 1990)  
107 through a visual assessment of the wood status (Lombardi et al. 2013). In a previous study, Petrillo  
108 et al. (2015) demonstrated that the Hunter classification is particularly suitable for describing  
109 changes in the physical-chemical characteristics of European larch (*Larix decidua* Mill.) and  
110 Norway spruce (*Picea abies* (L.) Karst.) deadwood in alpine environments. The physical-chemical  
111 properties of deadwood changed distinctly during decay and correlated well with the 5 decay  
112 classes. Furthermore, no substantial differences between spruce and larch decay patterns were  
113 found, although the wood chemistry of the living trees differed slightly between these two species  
114 (significant differences were found in the cellulose content, with 45.1% for spruce and 39.4% for  
115 larch; these differences were, however, negligible already in decay class 1; Petrillo et al., 2015).

116 European larch and spruce are widespread in the Alps. Although C-stocks in soils are substantial  
117 (e.g. Johnston et al., 2004), CWD is a non-negligible C reservoir in subalpine forests (Sandström et  
118 al., 2007). Consequently, it is thus very important to know which time scales are involved in CWD  
119 decay. Jebrane et al. (2014) showed that Scots pine is more decay resistant than European larch,  
120 which suggests that the decay rate of pine is lower. Some species of larch are, however, considered  
121 economically valuable due to their hard, heavy and decay-resistant wood (Parker, 1993), which  
122 implies that residence time of larch CWD should be longer.

123 The aim of our work was to find out; i) which time scales are involved in CWD decay of *P. abies*  
124 and *L. decidua* in the Alps and ii) how these time scales correlate with the five-decay class system.

125 We hypothesised that the CWD decay of these coniferous trees is relatively slow (due to, e.g. the  
126 nutrient availability for macro and micro-organisms being unfavourable).

127

128

## 129 **2 Materials and methods**

130

### 131 **2.1 Site description**

132 The study area is located in the north-eastern Italian Alps, in Val di Sole and Val di Rabbi (Fig. 1;  
133 Table 1). The climate of the valleys ranges from temperate to alpine (above the timberline), the  
134 mean annual temperature from 8.2 °C at the valley floor to about 0 °C at 2400 m a.s.l., and the  
135 mean annual precipitation from approximately 800 to 1300 mm (Sboarina and Cescatti, 2004). The  
136 geological substrate is paragneiss debris in all sites. The soil units are Cambisols, Umbrisols and  
137 Podzols (WRB: IUSS working group, 2014). The soil properties at each site could be taken from a  
138 previous study (Egli et al., 2006). The timberline is close to 2000 – 2200 m a.s.l., with the forests  
139 dominated by Norway spruce and, at the highest altitudes, by European larch.

140

### 141 **2.2 Sampling protocol**

142 Norway spruce and European larch CWD was sampled at eight sites ranging in altitude from 1200  
143 m a.s.l. to 2000 m a.s.l. In spring and summer 2013, wood cores from living trees and cross sections  
144 of CWD were taken from all sites. At each site, 5 or 6 living trees were sampled in two directions  
145 per each tree at 130 cm height (breast height) using an incremental corer (0.5 cm in diameter;  
146 Suunto, Finland). The wood cores were wrapped in paper and transported to the laboratory, where  
147 they were air dried, fixed onto a flat wooden support and sanded in order to obtain a smooth surface  
148 for tree-ring measurements. Before sampling, each CWD was first classified relative to the decay  
149 stage. The classification was done *in situ* using the five-class classification system of Hunter (1990)

(Table 2), which is based on visual, geometric and tactile features and considers the presence/absence of twigs and bark, the shape of the log section, and the deadwood structure. To sample CWD, a circular area of 50 m radius was explored at each plot. In total, 177 CWD samples were collected (46 of them were dated). At the highest sites, the forests consisted predominantly of larch trees. In addition, one lower site on the south-facing slope (S7) also had a predominantly larch forest. All other sites are spruce dominated. Samples were taken randomly either using a manual saw or, in more advanced stages of decay, simply by hand. If necessary, they were wrapped up with tape to preserve their structure during transport to the laboratory, where they were air dried and sanded. For CWD in more advanced decay stages (decay class 4 and 5), a 25 cm x 30 cm bag was filled. The samples were then oven-dried at 50 °C, but not sanded. To establish a master chronology, 83 wood cores were taken from living trees, 29 from larch and 54 from spruce. Two cores were taken from each tree. In three cases, one of the two cores taken from the same tree was too damaged to be measured (one at N02, one at S06 and one at S07). Furthermore, two outliers were excluded from the master chronology, namely one measured core at S07 and one at S08. CWD was dated using 46 cross sections from deadwood (18 from larch and 28 from spruce).

### 2.3 Dendrochronological dating

At each site, the 10 or 12 wood cores taken from living trees were used to build a reference (master) ring-width chronology for each species. Tree rings were first counted and then measured using the LINTAB tree-ring-width measurement device (RINNTECH e.K., Heidelberg, Germany), coupled together with a stereomicroscope (Leica, Germany). The two ring-width measurements from the same tree were first cross-checked and then incorporated into a single average master chronology for each species and for each site. To maximise the common signal, one outlier per species was excluded from the relative master chronology. These two tree-ring measurements exhibited a poor correlation with the other, probably due to an elevated number of missing rings. The statistical software TSAP-win<sup>TM</sup> (Time Series Analysis Program, RINNTECH e.K., Heidelberg, Germany)

176 was used to calculate the *Gleichläufigkeit*, GLK (Kaennel and Schweingruber, 1995), i.e. the  
177 agreement between two ring-width series. The correlations among all the ring-width series of living  
178 trees and CWD were statistically assessed using the software COFECHA (Holmes et al., 1986).  
179 EPS (expressed population signal; Wigley et al., 1984) was calculated using the statistic software R.  
180 The deadwood cross-sections were measured from the most external ring to the pith, along three or  
181 four different radial directions. The individual CWD series (i.e. floating chronologies) were  
182 matched to the master chronology of the corresponding species. We visually and statistically  
183 checked the deadwood series using the GLK to obtain the highest value with the master chronology  
184 and to date the year of death of the tree from which the deadwood originated.

185

## 186 **2.4 Radiocarbon dating**

187 The CWD of the decay classes 4 and 5 was too degraded to be dated through tree-ring analysis as  
188 their wood structure was too altered and the tree rings were no longer visible. In such cases, the  
189 outermost part of the CWD was sampled and  $^{14}\text{C}$ -dated (Fig. 2-A and 2-B). We selected a small  
190 fragment of 1 to 2 cm<sup>3</sup> in volume from the outermost part assumed to have contained the last- tree  
191 rings produced before the tree died (Fig. 2-C and 2-D). This small fragment was gently cleaned  
192 with a brush to remove any non-woody elements, such as particles of soil or vegetation like moss.  
193 The organic samples were cleaned using an acid-alkali-acid (AAA) treatment. The samples were  
194 then heated under vacuum in quartz tubes with CuO (oxygen source) to remove any absorbed CO<sub>2</sub>  
195 in the CuO. The tubes were evacuated, sealed and heated in the oven at 900 °C to obtain CO<sub>2</sub>. The  
196 CO<sub>2</sub> of the combusted sample was mixed with H<sub>2</sub> (1:2.5) and catalytically reduced over iron powder  
197 at 535 °C to elemental carbon (graphite). After reduction, the mixture was pressed into a target so  
198 that carbon ratios could be measured by Accelerator Mass Spectrometry (AMS) using the 0.2 MV  
199 radiocarbon dating facility (MICADAS) of the Laboratory of Ion Beam Physics at the Swiss  
200 Federal Institute of Technology of Zurich (ETHZ).

201 The calendar ages were obtained using the OxCal 4.2 calibration program (Bronk Ramsey, 2001,  
202 2009) based on the IntCal 13 calibration curve and for modern samples the Bomb  $^{13}\text{NH1}$  curve  
203 (Reimer et al., 2013; Hua et al., 2013) was used. Several samples (before 1950 AD) had a widely  
204 calibrated age range. For these samples, we used the age range with the highest probability of  
205 confining the time elapsed since death very strictly.

206

## 207 **2.5 Determining the cellulose and lignin**

208 To obtain  $\alpha$ -cellulose (Boettger et al., 2007), 10 mg of powdered wood were weighed in Teflon  
209 pockets for chemical and thermal treatments. All wood (sapwood and heartwood) was  
210 homogenised prior to chemical analysis. We decided to use this procedure, because it was not  
211 possible to distinguish between sapwood and heartwood for the most decayed stages. Samples were  
212 first washed in a 5% NaOH solution at 60 °C for two hours and then for an additional two hours  
213 with fresh 5 % NaOH solution (the NaOH solution was discarded each time), before finally being  
214 rinsed three times using boiling distilled water (see also Petrillo et al., 2015). The samples were  
215 then washed in a 7 %  $\text{NaClO}_2$  solution at 60 °C for 30 hours, changing the solution at least every 10  
216 hours and then rinsed three times with boiling distilled water. The pockets were dried in the oven at  
217 50 °C and the cellulose content was determined as the difference between the initial weight and  
218 dried samples. The so-called Klason lignin (lignin insoluble in strong acid; Dence and Lin, 1992)  
219 was determined gravimetrically after a sequential extraction in which 0.2 g of each sample was  
220 washed three times with 5 ml of distilled water at 80 °C. After each washing, the samples were  
221 centrifuged for 10 min at 4500 rpm, dried in the oven at 80 °C and washed three times with 5 ml of  
222 ethanol. They were then centrifuged again (10 min. at 4500 rpm) and the supernatant was  
223 discarded. After being dried at 60 °C in the oven, 60 mg of each sample were treated with 0.6 ml  
224 72 %  $\text{H}_2\text{SO}_4$  in a warm (30 °C) bath for one hour, and then, after adding 16.8 ml of distilled water,  
225 in an autoclave at 120 °C for one hour. Subsequently, the samples were filtered and the filtrate used  
226 to determine of the acid-soluble lignin. The insoluble lignin was dried in the oven at 105 °C and

227 determined as the difference between the dry and initial weight.

228 In total, the cellulose and lignin content was measured for 177 CWD samples.

229

## 230 **2.6 Estimating decomposition rate constants on the basis of density loss**

231 In a previous investigation (Petrillo et al., 2015), the density of the deadwood samples was  
232 measured. To estimate the decay constants, the average densities in class 1 and in class 5 (the  
233 earliest and latest decay stages) were used and the single-negative exponential model of Jenny et al.  
234 (1949) applied (see eq. 1). Equation 1 was then solved for the decay constant  $k$  according to  
235 equation 2:

$$236 \quad k = \frac{-\ln\left(\frac{x_t}{x_0}\right)}{t} \quad (2)$$

237 where  $x_t$  is the density of each deadwood sample at a given time (i.e. the estimated time elapsed  
238 since death), and  $x_0$  the initial density (0.45 g cm<sup>-3</sup> for *Picea abies* and 0.59 g cm<sup>-3</sup> for *Larix*  
239 *decidua*).

240 The density of all CWD samples was then compared to the related ages to derive the overall  
241 decomposition rates. A similar procedure was applied to cellulose and lignin to derive compound-  
242 specific decomposition rates of CWD.

243 Calculating mean residence time in decay classes from a single time point sample, rather than using  
244 longitudinal long-term data, tends to overestimate residence time due to a higher probability of  
245 inclusion of slow-decaying trees (Kruys et al., 2002). Consequently, snapshot sampling may  
246 overestimate the age and mean residence time of CWD. Thus, the decay rate could be  
247 underestimated. Calculating the overall CWD decay rates by using density values along a  
248 chronosequence risks, therefore, that a certain amount of error is introduced. This bias can be  
249 corrected using the proposed approach of Kruys et al. (2002). The mean residence time of CWD in  
250 a particular decay class is



$$E_m = \frac{\sum_{i=1}^N b_{mi}}{N} \quad (3)$$

where  $b_{mi}$  is the residence time of tree  $i$  in a specific decay class  $m$  and  $N$  = trees present during the time period. The estimator of  $E_m$  is:

$$\hat{E}_m = \frac{\sum_{i=1}^{n_m} \frac{b_{mi}}{c b_{mi}/T}}{\sum_{i=1}^{n_{tot}} \frac{1}{c l_i/T}} = \frac{n_m}{\sum_{i=1}^{n_{tot}} \frac{1}{l_i}} \quad (4)$$

with  $c$  = proportion of the logs existing at time point  $t$ ,  $n_m$  = number of trees from which samples were taken in decay class  $m$ ,  $n_{tot}$  is the total number of sampled trees and  $l_i$  is the total residence time of each tree across all decay classes. The expressions  $cb_{mi}/T$  and  $cl_i/T$  are the probabilities of including units  $b_{mi}$  and  $l_i$  in the sample, respectively. According to Kruys et al. (2002) it was assumed that all wood samples were taken half-way through their residence time in that class. The parameter  $l_i$  was calculated as  $age_i/x$ ;  $age_i$  is the measured time since death of tree  $i$  and

$$x = \frac{r_m}{2} + \sum_{k=1}^{m-1} r_k \quad (5)$$

where  $x$  is the sum of proportions,  $r_k$ , assigned to classes preceding the class of tree  $i$  plus 50% of the proportion assigned to tree  $i$ 's class,  $r_m$ .  $\hat{E}_m$  can be calculated iteratively for the different classes. Convergence occurred after 5 – 10 iterations.

## 3 Results

### 3.1 Living chronologies

Two master chronologies for spruce and larch were obtained extending over 164 and 141 years, respectively (Fig. 3). The spruce chronology ranged from 1848 to 2012 AD (Fig. 3) and the larch chronology from 1871 to 2012 AD. The tree-ring widths of the same species correlated well among

276 each other with a high GLK. When considering each individual plot, the GLK values were highest  
 277 at S09 (larch), with a mean GLK of 0.70 ( $\pm$  0.1) and lowest at N01 (spruce) with a mean GLK of  
 278 0.58 ( $\pm$  0.13). The series inter-correlation coefficients obtained using COFECHA were 0.535 for  
 279 spruce and 0.641 for larch (Pearson correlation, all series above 0.3281 were significant; 99%  
 280 confidence interval). The EPS values (Fig. 3B) were in most cases above (or close) to 0.85 (a  
 281 threshold value for noise-free chronology; Wigley et al., 1984), except for *Picea abies* for the  
 282 period of 1870 – 1910 AD. Spruce and larch, however, had quite different growth patterns with a  
 283 Pearson correlation coefficient of 0.274 when comparing the two species-specific master  
 284 chronologies. The spruce chronology indicated that the trees grew homogeneously throughout the  
 285 whole observation period, while larch seemed to be more sensitive to climate with marked high and  
 286 low growth periods (positive and negative pointer years, Fig. 3). Furthermore, the negative and  
 287 positive pointer years were not synchronous in the larch and spruce master chronologies. Even  
 288 though more larch trees were sampled at south-facing sites and at higher elevation, we can exclude  
 289 a bias due to an unbalanced sample distribution. Within the same homogenous climatic region  
 290 similar growth pattern are found (Carrer and Urbinati, 2006). The differences between the two  
 291 master chronologies are rather influenced by the different phenology of the two species. Larch is a  
 292 deciduous tree, with a deep rooting system, while spruce is evergreen and has a shallow root  
 293 system. Furthermore, the larch master chronology is cyclically influenced by outbreaks of the larch  
 294 bud defoliator *Zeiraphera diniana* Gn. that result in the abrupt occurrence of extremely narrow tree  
 295 rings which are not observed for spruce (Esper, 2007). The growth pattern of some trees, however,  
 296 differed considerably from that of the master chronology, possibly due to the specific growth  
 297 conditions of the individual trees, e.g. if their growth was very suppressed because of competition.  
 298 Such outliers were excluded from the chronologies.

299

### 300 3.2 Age of coarse woody debris (CWD)

301 Most of the samples of the decay classes 1 – 3 could be dendrochronologically dated, but those of  
302 decay classes 4 and 5 had to be radiocarbon dated because of the poorly preserved tree rings (Tables  
303 3 and 4). In the first three decay classes, the CWD ages of spruce and larch seem to be in a similar  
304 range. The values vary from 1 to 54 years. Interestingly, the average age of CWD does not seem to  
305 increase from class 1 to 3. The average age was around 10 – 20 years for all decay classes assuming  
306 a relatively fast decay. In decay classes 4 and 5, the average and maximum ages of CWD were  
307 usually higher for larch than for spruce. In decay class 4, spruce CWD has an average of about 42  
308 years (median 43 years; Fig. 4) and larch CWD an average of 87 years (median 45 years). In decay  
309 class 5, the average age of spruce CWD increases to 77 years and the age of larch CWD to 210  
310 years. This shows that larch wood, particularly in the decay classes 4 and 5, is much more resistant  
311 to rotting than spruce. Several CWDs had an age of around 200 years. The calibration of  
312 radiocarbon dates for such ages is, however, complicated by the so-called plateaus that give rise to a  
313 relatively wide range of calibrated ages. To minimise the array of possibilities, we used the age  
314 range with the highest probability for confining the time elapsed since death more strictly.

315

### 316 **3.3 Relations between year since death, decay class and physical-chemical properties of** 317 **deadwood**

318 The physico-chemical data for the CWD (n = 177) are given in Petrillo et al. (2015) and Tables 3  
319 and 4 so that the density and the cellulose and lignin contents could be plotted as a function of the  
320 decay class and age of the CWD (Fig. 5). Since the relationship between the age of the CWD and  
321 physical-chemical characteristics was rather stochastic for the decay classes 1 – 3, they were  
322 grouped and their average was used for further analysis. The decrease in density and cellulose  
323 concentrations and the simultaneous increase in lignin definitely proceed faster for the spruce CWD  
324 than for the larch CWD (Fig. 5). An exponential function best describes the trends in the cellulose  
325 and lignin concentrations with time.

326 The stage-based matrix model of Kruys et al. (2002) was applied to calculate the  $k$ -values (Table 5)  
 327 as a function of tree species and decay stage (summed decay classes)., Using the classical  
 328 chronosequence approach, the decay rate constants per year ( $y^{-1}$ ) were, furthermore, calculated for  
 329 each dated sample based on the density loss of spruce and larch CWD (Table 6). For spruce, we  
 330 obtained an average value of 0.018 ( $y^{-1}$ ) and for larch 0.012 ( $y^{-1}$ ; cf. Table 6). The  $k$ -values were  
 331 non-normally distributed. Using the Kruskal-Wallis statistical test, we assessed the effects of the  
 332 factors elevation, exposition, MAT (mean annual temperature), MAP (mean annual precipitation),  
 333 species and decay class on the  $k$ -values. None of these parameters significantly influenced the decay  
 334 rate constant. Nonetheless, the range of  $k$ -values on south-facing plots seem to be slightly higher  
 335 than those on the north-facing plots, which suggests the decomposition rates are faster on south-  
 336 exposed slopes (Fig. 6). In addition, the  $k$ -values were estimated by comparing the CWD density  
 337 with their age and by plotting an exponential regression curve (not shown). This approach resulted  
 338 in lower  $k$ -values: 0.012  $y^{-1}$  for spruce and 0.005  $y^{-1}$  for larch. The mean residence time and half-  
 339 lives are summarised in Table 7. The differences in mean residence time and rate constants between  
 340 Kruys' model and the more classical approach (chronosequence) using equation 1 are small (Table  
 341 6). Kruy's model gave slightly higher decay constants for Norway spruces (0.022  $y^{-1}$ ) and the same  
 342 values (0.018  $y^{-1}$ ) for European larch (variant a) in Table 6).

343

344

## 345 **4 Discussion**

346 Although the five-decay class system is well suited to describe changes in the physical and  
 347 chemical properties of deadwood (Lombardi et al., 2008), no real differences in the age of the CWD  
 348 classes 1 – 3 could be found. The CWD in decay class 4 and 5 was, however, clearly older. This  
 349 implies that the first three decay classes are not clearly related to deadwood age. Similarly,  
 350 Lombardi et al. (2013) found no relationship between the age of CWD and the chemical properties

351 of decay classes 1 – 3. The main explanation for this unexpected finding is that there is probably a  
352 time lag between the death of a standing tree and its contact with the soil (Kueppers et al., 2004;  
353 Zielonka, 2006; Lombardi et al., 2013). Standing dead trees, i.e. snags, can remain upright for  
354 several years and decay much more slowly than fallen dead trees (Yatskov et al., 2003). Such an  
355 effect overshadows a clear age trend in decay. If the species-specific fall rates were known the  
356 decay rates could be better assessed. Unfortunately, the fall rates of snags of the studied tree species  
357 are unknown at the investigated sites. To our knowledge, no data about fall rates of snags of either  
358 species, *Picea abies* (Norway spruce) and *Larix decidua* Mill. (European larch), are available. In  
359 this respect, the data situation in North America is much better. A good overview is given for  
360 example in Hilger et al. (2012) and Dixon (2015). According to Hilger et al. (2012), Engelmann  
361 spruce (*Picea engelmannii* Parry ex Engelm.) and subalpine larch (*Larix lyallii* Parl.) have similar  
362 snag fall rates. Due to morphological, ecological and physiological similarities, we have to assume  
363 (but we finally cannot prove it) that Norway spruce and European larch should exhibit a similar  
364 reaction to Engelmann spruce and subalpine larch. As a consequence, no particular difference in the  
365 fall rate between European larch and Norway spruce is to be expected. Therefore, difference in the  
366 decay rates between European larch and Norway spruce are hypothesised not to be due to different  
367 fall rates.

368 Angers et al. (2012), however, observed that the wood density in snags in boreal forests already  
369 decreases after a few years. Decay rates they calculated are comparable to those in our study. The  
370 density loss in standing dead trees could be due to the activity of cerambycid larvae, while the  
371 activity of the wood decomposers, mainly fungi, was impeded in snags due to the lack of moisture.  
372 The discrepancy between the macromorphology of deadwood (and consequently decay class) and  
373 the age of deadwood seems therefore to be related to the individual tree death history. Shortly after  
374 tree death, in fact, the wood is rapidly colonized by fungi (Zielonka, 2006). The CWD in classes 4  
375 and 5 showed a relation to deadwood age that seems to be species-specific since larch CWD is older  
376 than spruce in both classes. With respect to the CWD ages in our study, classes 1 to 3 appear to be a

377 single group, while classes 4 and 5 are different. The oldest sample (larch CWD) was about 244  
 378 years old – a surprisingly old age for wood lying on the forest floor (i.e. not buried). Spruce CWD  
 379 in decay classes 4 and 5 seem to be significantly younger than larch CWD. Few empirical  
 380 assessments of time since the death of a tree have been made in Europe. Krüger et al. (2014) used  
 381 both dendrochronology and radiocarbon dating to assess the time since death of Norway spruce in  
 382 Bavarian forests. They estimated a total residence time of 61 to 62 years for this species. Our values  
 383 are slightly lower. One major problem in determining the age using  $^{14}\text{C}$  are the sometimes large age  
 384 ranges obtained after calibration (due to plateaus) for samples having a pre-bomb age. We used the  
 385 ranges with the highest probabilities (varying from 50 to 82.2%; Table 4; commonly the age 1- $\sigma$   
 386 range, i.e. 68% is considered) for CWD dated to the time period before the bomb peak.  
 387 Consequently, this procedure introduces an uncertainty. According to Krüger et al. (2014),  
 388 radiocarbon analysis and dendrochronological cross-dating revealed a similar year of tree death for  
 389 samples having a post-bomb age. The results of Krüger et al. (2014) suggest that both methods are  
 390 suitable for the age determination of CWD. In Atlantic Canada, Campbell and Laroque (2007)  
 391 found an age of 56 to 84 years (depending on the investigated sites) in the latest decay stage (decay  
 392 class 5; Black spruce and Balsam fir). Lombardi et al. (2008) estimated stumps of beech and silver  
 393 fir in decay class 3 to be 55 and 59 years which is close to our findings.

394 The decay rates reflect the determined ages of the CWD; and spruce therefore had a higher decay  
 395 rate constant than larch. Consequently, decay rates are species specific due to, among others things,  
 396 the initial differences in the physical-chemical properties of the wood of the living trees and in  
 397 environmental factors. Larch has, for example, a higher density (cf. Fig. 5) and a lower nutrient  
 398 content than spruce (Petrillo et al., 2015). Shorohova et al. (2014) also found that decay rates can  
 399 strongly vary among tree species. The decay rate (i.e.  $0.032\text{ y}^{-1}$ ) they found for spruce was slightly  
 400 higher than that in our study (Fig. 6). The variability of the decay rates given in the literature may  
 401 also arise from using different mathematical models or different methods to determine wood density  
 402 or the age of the CWD. According to Hale and Pastor (1998), the decay rates of oak and maple logs

403 (in a temperate forest) varied between 0.00 and 0.18  $\text{y}^{-1}$  (their dating of the logs, however, was  
 404 based on estimates). The decay rates of tree species in a Mediterranean area (Australia; Brown et  
 405 al., 1996) varied in the range of 0.05 up to 0.22  $\text{y}^{-1}$ , while in a cool-continental climate (Alban and  
 406 Pastor, 1993), decay rates were 0.042 and 0.055 for red and jack pine, respectively, 0.07 for spruce  
 407 and 0.08  $\text{y}^{-1}$  for aspen. Fukusawa et al. (2014) estimated decay rates by using the annual input of  
 408 CWD divided by the CWD accumulation, and obtained a value of 0.036  $\text{y}^{-1}$ . With the  
 409 chronosequence approach, however, the rates were in the order of 0.020 – 0.023  $\text{y}^{-1}$ .  
 410 The determined decay rates for spruce and larch in our investigation seem to be very low (Table 6).  
 411 As pointed out by Kruys et al. (2002), the chronosequence approach, and thus the snapshot  
 412 sampling, may overestimate the CWD age and consequently residence time. Thus, the decay rate  
 413 may be underestimated. It seems, however, that this error is not overwhelmingly distinct in our case  
 414 or even absent. The approach according to Kruys et al. (2002) and variant a) in Table 6 gave similar  
 415 results. The regression approach (variant b) in Table 6) probably slightly underestimated the decay  
 416 rates.  
 417 Using mass losses instead of density losses to estimate the decay rates may result in higher values,  
 418 because the losses for fragmentation are added to the mineralisation losses (Yin, 1999). This might  
 419 explain why our decay rate constants were lower than those in some other studies (Rock et al.,  
 420 2008; Herrmann et al., 2015). Moreover, the decay rates are sensitive, at a regional scale, to climatic  
 421 conditions such as temperature and precipitation (Shorohova et al., 2014), although the decay rates  
 422 for a mean annual temperature of 0 to 10 °C are, however, quite similar, and rates below 0.04  $\text{y}^{-1}$  are  
 423 often reported (Mackensen et al., 2003). Soil temperature was found to be the main explanatory  
 424 variable for differences in the decay rates of standard wood, such as aspen and pine (Risch et al.,  
 425 2013). Although the data are too limited to draw clear conclusion, some of the differences in the  
 426 decay rates we observed are likely to be due to environmental factors. On south-facing sites, for  
 427 instance, we found that the decay rates were slightly, but not significantly, higher than those on  
 428 north-facing sites (Fig. 6), which is comparable to Shorohova's et al. (2014) observations.

429 Although our measured  $k$  values are very low, they fit reasonably well to those of the recent  
 430 compilation of Russel et al. (2015). For environments having a mean annual temperature of  $< 10$   
 431  $^{\circ}\text{C}$ , the decay rate constants are usually  $< 0.1$  (median value is 0.027 for such sites). The  
 432 compilation of Russel et al. (2015), however, only considers two sites having *Picea abies* ( $k$  values  
 433  $= 0.044$  and  $0.027$ ; Krankina et al., 1999; Næsset, 1999) and none for larch. Together with our  
 434 results, a residence time of about 20 – 90 years for *Picea abies* in subalpine (boreal) climates might  
 435 be suggested.

436 The concentrations of cellulose and lignin in the CWD are given as a function of time in Fig. 5. Due  
 437 to the faster decomposition of cellulose, lignin is relatively enriched. Lignin, however, also  
 438 decomposes with time. To unravel the decay behaviour of these compounds, a multiple-exponential  
 439 model was applied (Means et al., 1985; Mackensen et al., 2003), with the general form:

$$440 \quad x = x_1 e^{-k_1 t} + x_2 e^{-k_2 t} \dots + x_n e^{-k_n t} \quad (6)$$

441 where  $x_i$  is the density or mass of deadwood at a given time and  $x_{1..n}$  are partitioned parameters. The  
 442 portioning of cellulose and lignin is solved graphically using their mass per unit volume over time,  
 443 and fitting them to an exponential regression curve. From this, the half-life of cellulose or lignin in  
 444 the CWD could be calculated:

$$445 \quad t_{1/2} = \frac{\ln(1/2)}{-k} \quad (7)$$

446 where  $t_{1/2}$  is the half-life and  $k$  is the decay constant (obtained from the exponential regression  
 447 curve). Using the  $k$ -values in Fig. 7, the following half-lives were obtained:

- 448 a) for cellulose: 21 years (spruce) and 50 years (larch)
- 449 b) for lignin: 91 years (spruce) and 481 years (larch)

450 Means et al. (1985) were able to derive  $k$ -values for cellulose values of  $0.0109$  to  $0.0117 \text{ y}^{-1}$  for  
 451 Douglas-fir logs (in a cool to temperate climate), although age determination (or estimation) was  
 452 done differently. This would give rise to half-lives in the range of 59 to 64 years. With  $k$ -values in  
 453 the range of  $0.0039$  to  $0.0045 \text{ y}^{-1}$  (Means et al., 1985), the half-life of lignin would be in the range



454 of 154 – 178 years. In this specific case, the overall decay rates were between 0.006 and 0.0073 y<sup>-1</sup>.  
455 Although cellulose is relatively easily degradable by (micro)organisms, it may persist astonishingly  
456 long in larch trees (several decades). Lignin may have a half-life of more than hundred years. These  
457 half-lives may be shorter if the decay is related to mass losses and not to density.  
458 In decay classes 4 and 5, the CWD starts to become more and more part of the soil. The further fate  
459 of CWD compounds strongly depends on their interaction with the mineral soil. The introduced  
460 organic matter into soils can be either further degraded or stabilised to a certain extent. The  
461 persistence of organic matter in soils is largely due to complex interactions between the organic  
462 matter and its environment, such as the interdependence of compound chemistry, reactive mineral  
463 surfaces, climate, water availability, soil acidity, soil redox state and the presence of potential  
464 degraders in the immediate micro-environment (Schmidt et al., 2011). Together with physical  
465 protection, organo-mineral interactions are generally thought to be the main mechanism for SOM  
466 stabilisation (e.g., Nierop et al., 2002; Kleber et al., 2005; Marschner et al., 2008).

467

468

## 469 **5 Conclusions**

470 The first 3 decay classes do not seem to reflect the age of the CWD, but they are relevant for the  
471 description of its decay stage. The time lag between the death of a standing tree and its contact with  
472 the soil overshadows a clear age trend. Taking classes 1 – 3 as one group and relating them to the  
473 decay classes 4 and 5, a time trend with increasing decay stage can then be detected. This time trend  
474 also closely correlates to the wood density, and the cellulose and lignin content. The oldest CWD  
475 age of a larch tree reached the considerable age of 244 years. We used a chronosequence approach  
476 and applied several calculation techniques to estimate the overall decay rate constants of European  
477 larch and Norway spruce. The stage-based matrix model of Kruys et al. (2002) that corrects for  
478 sampling bias was in good agreement with the often-used single-negative-exponential model. The

479 regression approach probably underestimated slightly the decay rates. The decay rate constant for  
480 spruce seems to be in the range of 0.018 to 0.022 ( $\text{y}^{-1}$ ) and for larch it is about 0.012 ( $\text{y}^{-1}$ ). The rates  
481 seemed to be slightly higher on south-facing sites (although this was not statistically significant).  
482 An effect of the altitude on the decay rates was, however, not discernible. Using the dating  
483 approach (dendrochronology and  $^{14}\text{C}$ -dating), the behaviour of cellulose and lignin as a function of  
484 time could be assessed. Our findings demonstrate that lignin in larch may persist particularly long,  
485 with a mean residence time of  $> 100$  years. This indicates that turnover rates of CWD organic  
486 matter are even in a comparable range to that of SOM.  
487 More empirical data is, however, needed to ascertain our findings. A major issue is that fall rates  
488 between European Larch and Norway spruce could not be compared. Furthermore, the preparation  
489 and precise dating of CWD is time-consuming, cost intensive and in some cases also difficult  
490 (particularly samples with a pre-bomb age in decay classes 4 and 5). Since CWD represents an  
491 important forest carbon pool, improving the informative potential of the decay classes (including  
492 the dating of the CWD) would contribute to sustainable forest management and make carbon  
493 accounting easier.

494

495

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505

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**Table 1.** Characteristics of the study sites.

| Plot ID                   | Elevation<br>(m a.s.l.) | Aspect<br>(°N) | Slope<br>(°) | MAP <sup>a</sup><br>(mm y <sup>-1</sup> ) | Parent material                        | Dominating tree<br>species | Land use   | Soil classification (WRB)<br>(Egli et al., 2006)       |
|---------------------------|-------------------------|----------------|--------------|---|--|----------------------------|--|--|
| <i>North-facing sites</i> |                         |                |              |   |  |                            |  |  |
| N01                       | 1180                    | 340            | 31           | 950                                       | Paragneiss debris                      | <i>Picea abies</i>         | Natural forest<br>(ecological forestry)                | Chromi-Episkeletic<br>Cambisol (Dystric)               |
| N02                       | 1390                    | 0              | 28           | 1000                                      | Paragneiss debris                      | <i>Picea abies</i>         | Natural forest<br>(ecological forestry)                | Chromi-Episkeletic<br>Cambisol (Dystric)               |
| N03                       | 1620                    | 0              | 29           | 1060                                      | Paragneiss debris                      | <i>Picea abies</i>         | Natural forest<br>(ecological forestry)                | Chromi-Endoskeletal<br>Cambisol (Dystric)              |
| N04                       | 1930                    | 20             | 12           | 1180                                      | Paragneiss debris,<br>moraine material | <i>Larix decidua</i>       | Originally used as<br>pasture                          | Episkeletic Podzol                                     |
| <i>South-facing sites</i> |                         |                |              |   |  |                            |  |  |
| S06                       | 1185                    | 160            | 31           | 950                                       | Paragneiss debris                      | <i>Picea abies</i>         | Ex-coppice, natural<br>forest (ecological<br>forestry) | Episkeleti-Endoleptic<br>Cambisol (Chromi-<br>Dystric) |
| S07                       | 1400                    | 145            | 33           | 1000                                      | Paragneiss debris                      | <i>Larix decidua</i>       | Natural forest<br>(ecological forestry)                | Dystri-Endoskeletal<br>Cambisol                        |
| S08                       | 1660                    | 210            | 33           | 1060                                      | Paragneiss debris                      | <i>Picea abies</i>         | Natural forest<br>(ecological forestry)                | Skeletal Umbrisol                                      |
| S09                       | 1995                    | 160            | 25           | 1180                                      | Paragneiss debris                      | <i>Larix decidua</i>       | Ex pasture, natural<br>forest                          | Skeletal Umbrisol                                      |

<sup>a</sup>MAP = mean annual precipitation (Sboarina and Cescatti, 2004)

**Table 2.** The five decay-class system of log decomposition (according to Hunter, 1990).

| Log features            | Decay classes                            |                            |                                     |                          |   |
|-------------------------|--|----------------------------|-------------------------------------|--------------------------|---|
|                         | 1  | 2                          | 3                                   | 4                        | 5   |
| Bark                    | Intact                                   | Partially absent           | Absent                              | Absent                   | Absent  |
| Twigs                   | Present                                  | Partially absent or absent | Absent                              | Absent                   | Absent  |
| Shape of radial section | Round                                    | Round                      | Round                               | Oval                     | Very oval                                     |
| Colour                  | Original                                 | Original                   | Faded in the external part          | Reddish brown or faded   | Reddish or faded                              |
| Texture of wood         | Intact                                   | Intact                     | Soft outer layer, intact inner part | Small pieces, soft       | Powdery or fibrous, very soft                 |
| Contact with soil       | Log elevated on what remains of branches | Log in contact with soil   | Log in contact with soil            | Log in contact with soil | Log in contact with soil and partially buried |

**Table 3.** Typical properties and ages of Norway spruce and European larch CWD in class 1 – 3. Ages were obtained mostly from dendrochronological measurements and a few\* from  $^{14}\text{C}$ -dating (Detail of  $^{14}\text{C}$ -dating cf. Appendix A).

| Plot | Tree species   | Decay class | Density (g cm <sup>-3</sup> ) | Cellulose (%) | Lignin (%) | Year of death | CWD age |
|------|----------------|-------------|-------------------------------|---------------|------------|---------------|---------|
| N03  | Norway spruce  | 1           | 0.32                          | 34.8          | 22.4       | 2009          | 4       |
| S08  | Norway spruce  | 1           | 0.40                          | 31.3          | 33.2       | 1992          | 21      |
| N01  | Norway spruce  | 1           | 0.45                          | 43.4          | 22.0       | 1988          | 25      |
| N02  | Norway spruce  | 1           | 0.44                          | 41.4          | 23.3       | 1969          | 44      |
| N03  | Norway spruce  | 2           | 0.39                          | 41.4          | 35.9       | 2006          | 7       |
| N03  | Norway spruce  | 2           | 0.44                          | 28.4          | 25.0       | 2004          | 9       |
| N03  | Norway spruce  | 2           | 0.39                          | 27.8          | 25.9       | 2004          | 9       |
| S08  | Norway spruce  | 2           | 0.36                          | 38.2          | 23.1       | 2003          | 10      |
| N02  | Norway spruce  | 2           | 0.11                          | 39.2          | 14.2       | 1996          | 17      |
| N03  | Norway spruce  | 2           | 0.43                          | 40.8          | 21.5       | 1993          | 20      |
| N01  | Norway spruce  | 2           | 0.39                          | 28.2          | 24.3       | 1970          | 43      |
| N02  | Norway spruce  | 2           | 0.67                          | 27.8          | 25.9       | 1959          | 54      |
| N03  | Norway spruce  | 3           | 0.48                          | 43.6          | 23.4       | 2012          | 1       |
| N03  | Norway spruce  | 3           | 0.38                          | 36.6          | 24.2       | 2005          | 8       |
| N03  | Norway spruce  | 3           | 0.39                          | 37.4          | 10.7       | 2005          | 8       |
| N01  | Norway spruce  | 3           | 0.30                          | 22.3          | 35.1       | 1979          | 34      |
| N02  | Norway spruce  | 3           | 0.48                          | 33.5          | 24.6       | 1970          | 43      |
| S09  | European larch | 1           | 0.60                          | 37.2          | 21.1       | 2010          | 3       |
| N04  | European larch | 1           | 0.59                          | 44.2          | 16.9       | 1973          | 40      |
| S07* | European larch | 1           | 0.31                          | 21.2          | 39.6       | 2007          | 6       |
| S07  | European larch | 2           | 0.58                          | 20.2          | 38.0       | 2010          | 3       |
| S09  | European larch | 2           | 0.53                          | 37.3          | 31.0       | 2000          | 13      |
| S07* | European larch | 2           | 0.30                          | 30.4          | 40.6       | 2003          | 10      |
| S07* | European larch | 3           | 0.27                          | 6.7           | 63.0       | 2004          | 9       |
| S09* | European larch | 3           | 0.60                          | 4.2           | 40.8       | 1973          | 40      |
| S09* | European larch | 3           | 0.33                          | 23.3          | 58.4       | 1968          | 45      |

**Table 4.** Typical properties and radiocarbon data of the deadwood samples (decay classes 4 and 5) as a function of site and tree species.

| UZH     | ETH number | Sample | Site | Tree           | Decay | Density               | Cellulose | Lignin | <sup>14</sup> C-age | ±1σ | δ <sup>13</sup> C | ±δ <sup>13</sup> C | cal AD    | Average age <sup>1)</sup> | cal AD <sup>2)</sup>  | Average age <sup>1)</sup> |
|---------|------------|--------|------|----------------|-------|-----------------------|-----------|--------|---------------------|-----|-------------------|--------------------|-----------|---------------------------|-----------------------|---------------------------|
| number  |            | code   |      | species        | class | (g cm <sup>-3</sup> ) | (%)       | (%)    | years               |     | ‰                 | ‰                  | 2 σ       | years                     | years (probability)   | years                     |
| UZ 6210 | ETH-56612  | 37A    | N4   | European larch | 4     | 0.26                  | 34.6      | 27.9   | -2931               | 29  | -23.6             | 1                  | 1962-1974 | 45                        |                       |                           |
| UZ 6211 | ETH-56613  | 34A    | N4   | European larch | 4     | 0.40                  | 1.0       | 47.2   | 170                 | 31  | -24.4             | 1                  | 1658-1950 | 209                       | 1720-1819<br>(50%)    | 244                       |
| UZ 6213 | ETH-56615  | 50A    | S9   | European larch | 4     | 0.15                  | 2.3       | 43.2   | -659                | 31  | -26.5             | 1                  | 1957-2003 | 33                        |                       |                           |
| UZ 6219 | ETH-56853  | 95A    | S7   | European larch | 4     | 0.21                  | 16.7      | 38.4   | -860                | 25  | -25.5             | 1                  | 1957-1998 | 36                        |                       |                           |
| UZ 6227 | ETH-56861  | 209    | S7   | European larch | 4     | 0.33                  | 0.0       | 47.2   | -2545               | 25  | -25.3             | 1                  | 1962-1976 | 44                        |                       |                           |
| UZ 6228 | ETH-56862  | 214    | S7   | European larch | 4     | 0.33                  | 16.5      | 28.7   | 60                  | 25  | -23.9             | 1                  | 1695-1919 | 206                       | 1867-1919<br>(53.3%)  | 120                       |
| UZ 6212 | ETH-56614  | 45B    | S9   | European larch | 5     | 0.34                  | 25.9      | 29.4   | 183                 | 31  | -27               | 1                  | 1650-1950 | 213                       | 1726-1815<br>(51.5%)  | 243                       |
| UZ 6224 | ETH-56858  | 202    | S9   | European larch | 5     | 0.25                  | 0.0       | 58.1   | 140                 | 25  | -28.9             | 1                  | 1669-1944 | 207                       | 1798-1944<br>(52.6 %) | 142                       |
| UZ 6264 | ETH-60747  | 33     | N4   | European larch | 5     | 0.28                  | 0.0       | 49.4   | 185                 | 25  | -29.4             | 1                  | 1656-1950 | 220                       | 1728-1810<br>(54.7 %) | 244                       |
| UZ 6214 | ETH-56616  | 69A    | S6   | Norway spruce  | 4     | 0.13                  | 23.3      | 25.2   | -1331               | 30  | -31.3             | 1                  | 1958-1989 | 40                        |                       |                           |
| UZ 6215 | ETH-56849  | 72A    | S6   | Norway spruce  | 4     | 0.37                  | 0.0       | 51.7   | -2120               | 25  | -23.6             | 1                  | 1961-1980 | 43                        |                       |                           |
| UZ 6216 | ETH-56850  | 84A    | S8   | Norway spruce  | 4     | 0.16                  | 32.4      | 29.1   | -4080               | 25  | -27               | 1                  | 1966-1967 | 47                        |                       |                           |
| UZ 6220 | ETH-56854  | 97B    | N2   | Norway spruce  | 4     | 0.26                  | 28.1      | 36.1   | -3720               | 25  | -31.4             | 1                  | 1967-1968 | 46                        |                       |                           |
| UZ 6221 | ETH-56855  | 98A    | N3   | Norway spruce  | 4     | 0.26                  | 0.0       | 67.0   | -290                | 25  | -19.7             | 1                  | 1955-2009 | 31                        |                       |                           |
| UZ 6226 | ETH-56860  | 206    | N3   | Norway spruce  | 4     | 0.29                  | 28.5      | 20.5   | -2150               | 25  | -23.9             | 1                  | 1962-1979 | 43                        |                       |                           |
| UZ 6217 | ETH-56851  | 87A    | S8   | Norway spruce  | 5     | 0.13                  | 1.5       | 66.8   | 130                 | 25  | -26.1             | 1                  | 1677-1940 | 205                       | 1800-1940<br>(59.5%)  | 143                       |
| UZ 6218 | ETH-56852  | 89A    | S8   | Norway spruce  | 5     | 0.27                  | 17.6      | 27.7   | -615                | 25  | -24.6             | 1                  | 1956-2004 | 33                        |                       |                           |
| UZ 6222 | ETH-56856  | 106A   | N1   | Norway spruce  | 5     | 0.19                  | 4.3       | 68.5   | -1665               | 25  | -25.2             | 1                  | 1959-1984 | 42                        |                       |                           |
| UZ 6223 | ETH-56857  | 197    | N1   | Norway spruce  | 5     | 0.19                  | 0.0       | 40.2   | -4595               | 25  | -24               | 1                  | 1963-1965 | 49                        |                       |                           |
| UZ 6225 | ETH-56859  | 205    | N2   | Norway spruce  | 5     | 0.19                  | 0.0       | 44.3   | 10                  | 25  | -22.9             | 1                  | 1699-1916 | 206                       | 1879-1916<br>(82.2 %) | 116                       |

<sup>1)</sup> Calculated as the mean value between the maximum and minimum age (2 σ). For this range of years (2 σ), associated probabilities are summed to 95.4 %

<sup>2)</sup> For samples dated in the period before the bomb peak and giving a wide calibrated age range, the age is also calculated for the most important calibrated time-range associated to the highest, corresponding probability (in brackets)

**Table 5.** Mean residence time and decay constants calculated using the stage-based matrix model of Kruys et al. (2002)

| Decay class | No of samples |       | Mean residence time |       | Decay constant ( $y^{-1}$ ) |       |
|-------------|---------------|-------|---------------------|-------|-----------------------------|-------|
|             | Spruce        | Larch | Spruce              | Larch | Spruce                      | Larch |
| 1           | 4             | 3     | 77                  | 80    | 0.013                       | 0.012 |
| 1+2         | 8             | 3     | 36                  | 47    | 0.027                       | 0.021 |
| 1+2+3       | 4             | 3     | 28                  | 67    | 0.036                       | 0.015 |
| 1+2+3+4     | 6             | 6     | 63                  | 116   | 0.016                       | 0.009 |
| 1+2+3+4+5   | 5             | 3     | 63                  | 254   | 0.016                       | 0.004 |

**Table 6.** CWD decay parameters based on a) equation 1, b) the regression approach and c) stage-based matrix model of Kruys et al. (2002)

|                | Average decay constant $k$<br>( $y^{-1}$ ) | Residence time*<br>(y) | Half-life*<br>(y) |
|----------------|--|------------------------|-------------------|
| a)             |  |                        |                   |
| Norway spruce  | 0.018                                      | 56                     | 39                |
| European larch | 0.012                                      | 83                     | 58                |
| b)             |  |                        |                   |
| Norway spruce  | 0.012                                      | 84                     | 58                |
| European larch | 0.005                                      | 222                    | 154               |
| c)             |  |                        |                   |
| Norway spruce  | 0.022                                      | 45                     | 32                |
| European larch | 0.012                                      | 83                     | 58                |

\*calculated from the average decay constant

**Appendix A.** Radiocarbon data of the deadwood samples of the decay classes 1 – 3.

| UZH number | ETH number | Sample code | Site | Tree species   | Decay<br>class | C14 age | $\pm 1\sigma$ | $\delta^{13}\text{C}$<br>‰ | $\pm\delta^{13}\text{C}$<br>‰ | Cal AD<br>$\pm 1\sigma$ | Average age<br>years |
|------------|------------|-------------|------|----------------|----------------|---------|---------------|----------------------------|-------------------------------|-------------------------|----------------------|
| UZ-6258    | ETH-60741  | L_10_c1_1   | S7   | European Larch | 1              | -435    | 25            | -25.7                      | 1                             | 2006-2009               | 6                    |
| UZ-6260    | ETH-60743  | S07_dc2_92  | S7   | European Larch | 2              | -590    | 25            | -26.9                      | 1                             | 2002-2004               | 10                   |
| UZ-6261    | ETH-60744  | S07_dc3_96  | S7   | European Larch | 3              | -545    | 25            | -26.4                      | 1                             | 2003-2005               | 9                    |
| UZ-6262    | ETH-60745  | S09_cl3_46  | S9   | European Larch | 3              | -2865   | 25            | -29.3                      | 1                             | 1973-1974               | 40                   |
| UZ-6263    | ETH-60746  | S09_cl3_48  | S9   | European Larch | 3              | -2775   | 25            | -23.8                      | 1                             | 1962-1974               | 45                   |

<sup>1)</sup> Calculated as the mean value between the maximum and minimum age (1  $\sigma$ ). For this range of years (1  $\sigma$ ), associated probabilities summed to 68.2 %



677 **Figure captions**

678

679 **Fig. 1.** Location of the study area with the major vegetation units and investigation sites. Data  
680 source: Museo delle Scienze (Trento), CORINE Landcover (Joint Research Center of the European  
681 Union) and scilands GmbH. The site label N indicates north-facing sites and S south-facing sites.

682

683 **Fig. 2.** Cross section of (A) spruce deadwood in the field (site N03) and (B) larch deadwood (site  
684 S07). Examples (C and D) of deadwood fragments classified as decay class 4 dated using  
685 radiocarbon (outermost part of the wood piece).

686

687 **Fig. 3.** Master chronologies for spruce and larch to cross-date the deadwood (A) and the expressed  
688 population signal (EPS) for segments of constant periods (B). A noise-free chronology is achieved  
689 with an EPS > 0.85 (dashed line; Wigley et al., 1984)

690

691 **Fig. 4.** Box plots of the larch and spruce deadwood age as a function of decay class.

692

693 **Fig. 5.** Relation between the age of spruce and larch CWD and density (A), cellulose % (B) and  
694 lignin % (C). The decay classes 1 – 3 were grouped together due to their similar age (Fig. 4).

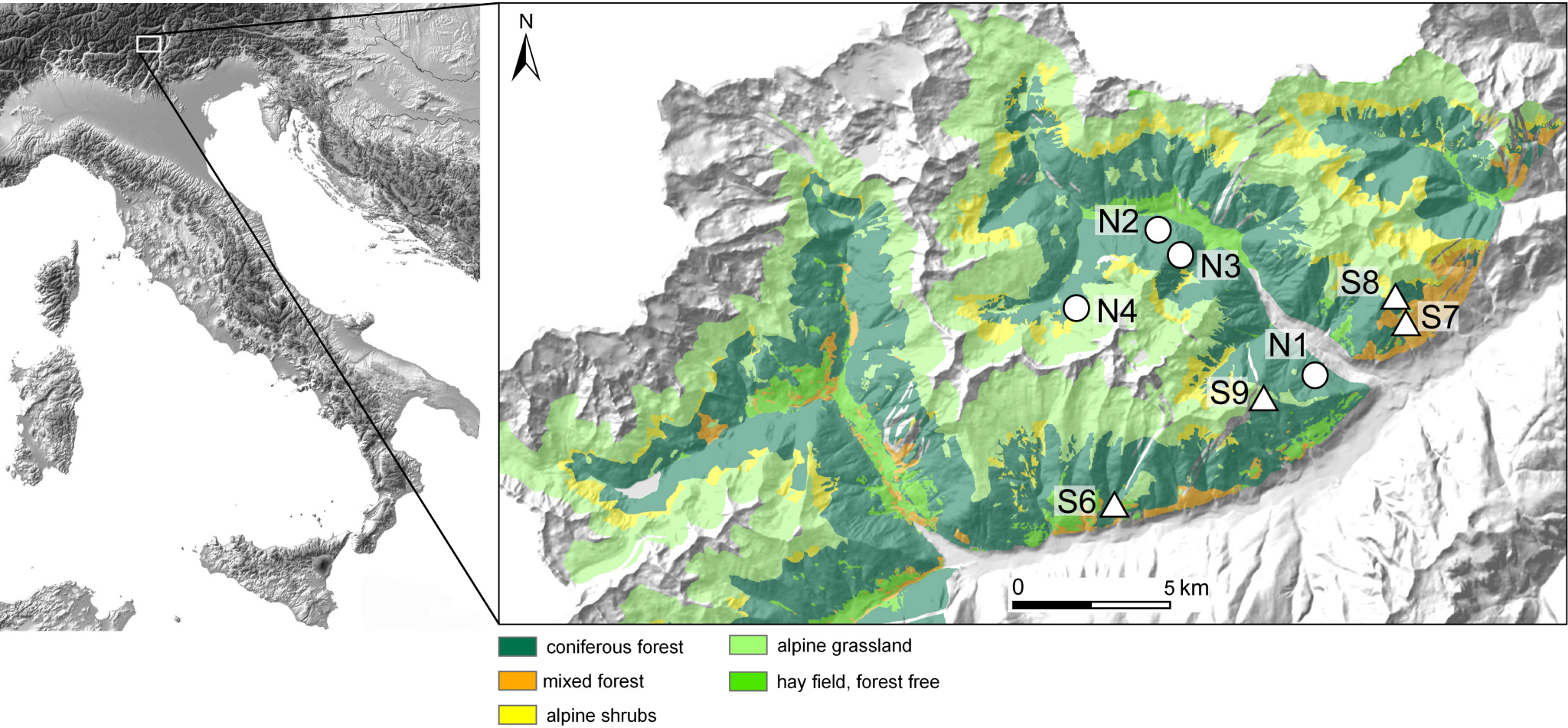
695

696 **Fig. 6.** Calculated decay rate constants (k) as a function of tree species and site exposure.

697

698 **Fig. 7.** Empirically determined exponential regression curves (principle of multiple-exponential  
699 model) for partitioning the decay behaviour of cellulose (A) and lignin (B).

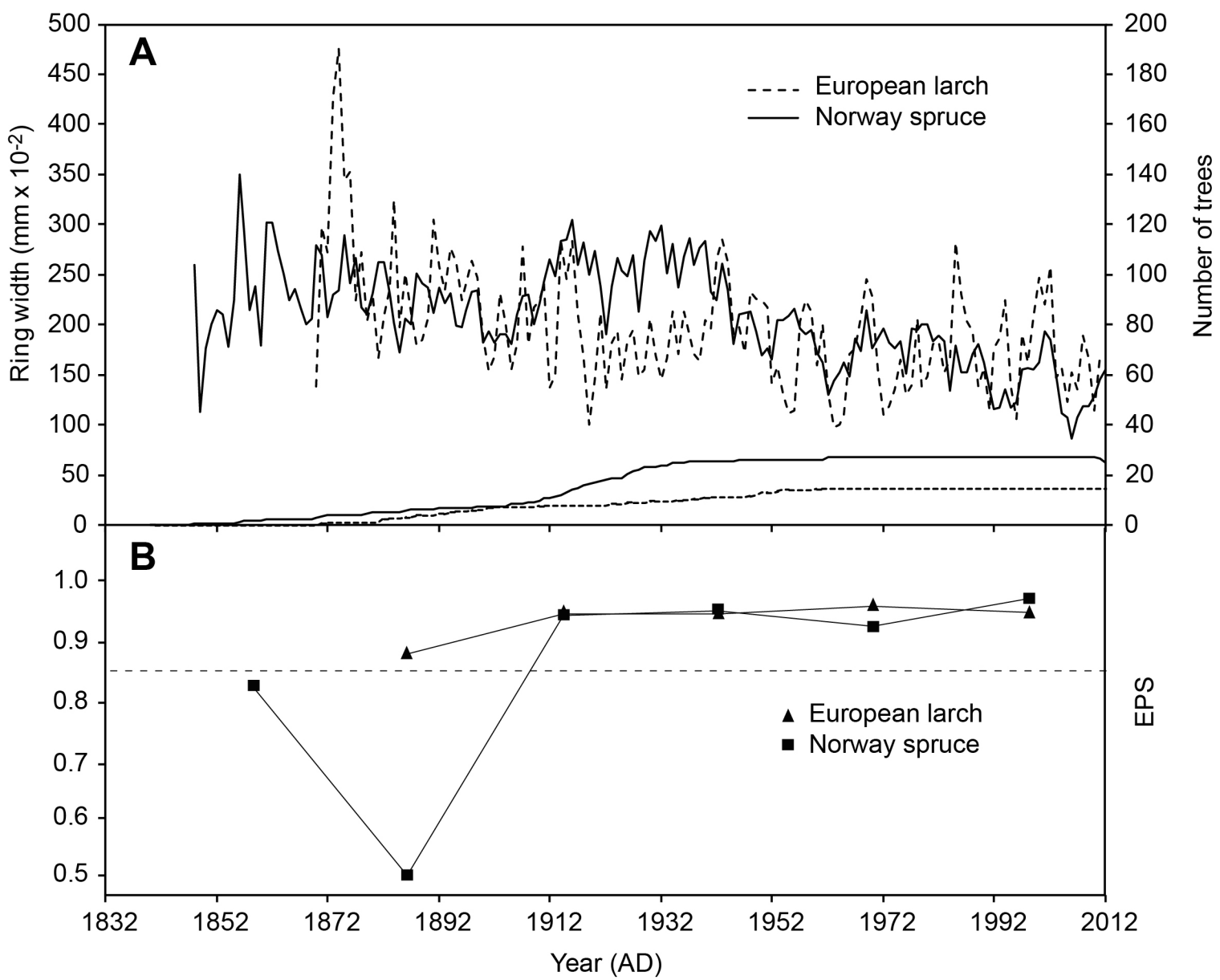
Fig. 1



**Fig. 2**



**Fig. 3**



**Fig. 4**

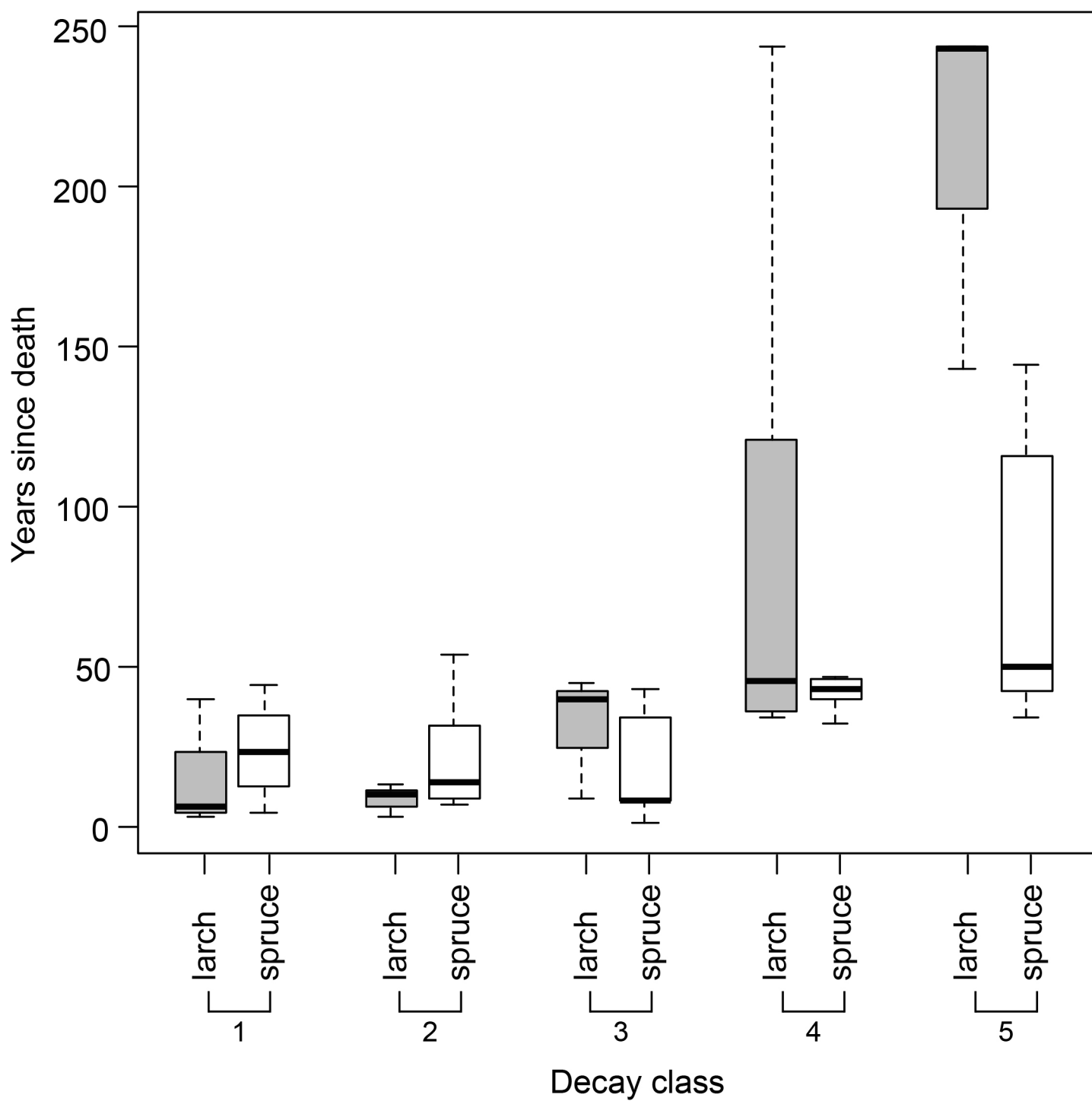
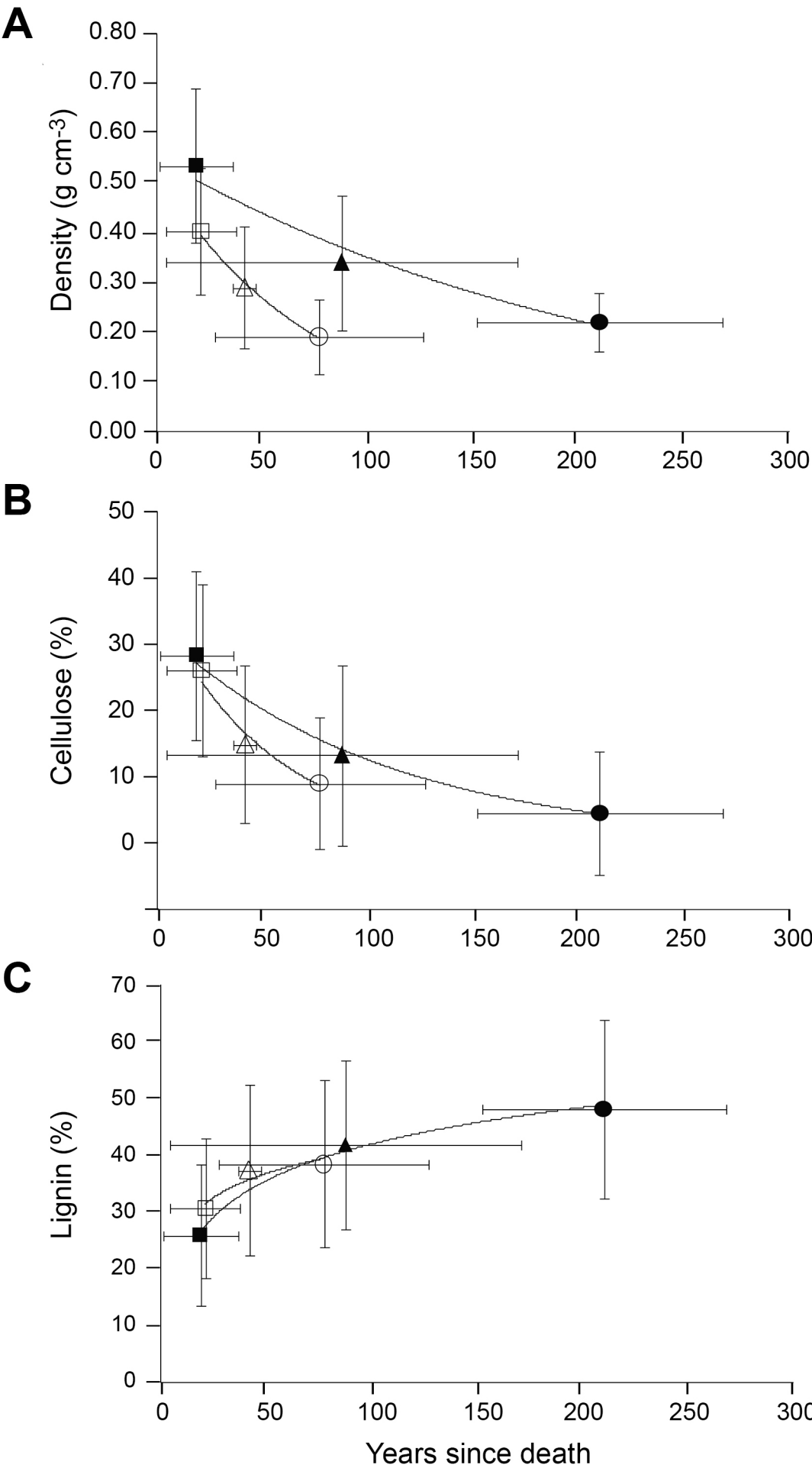
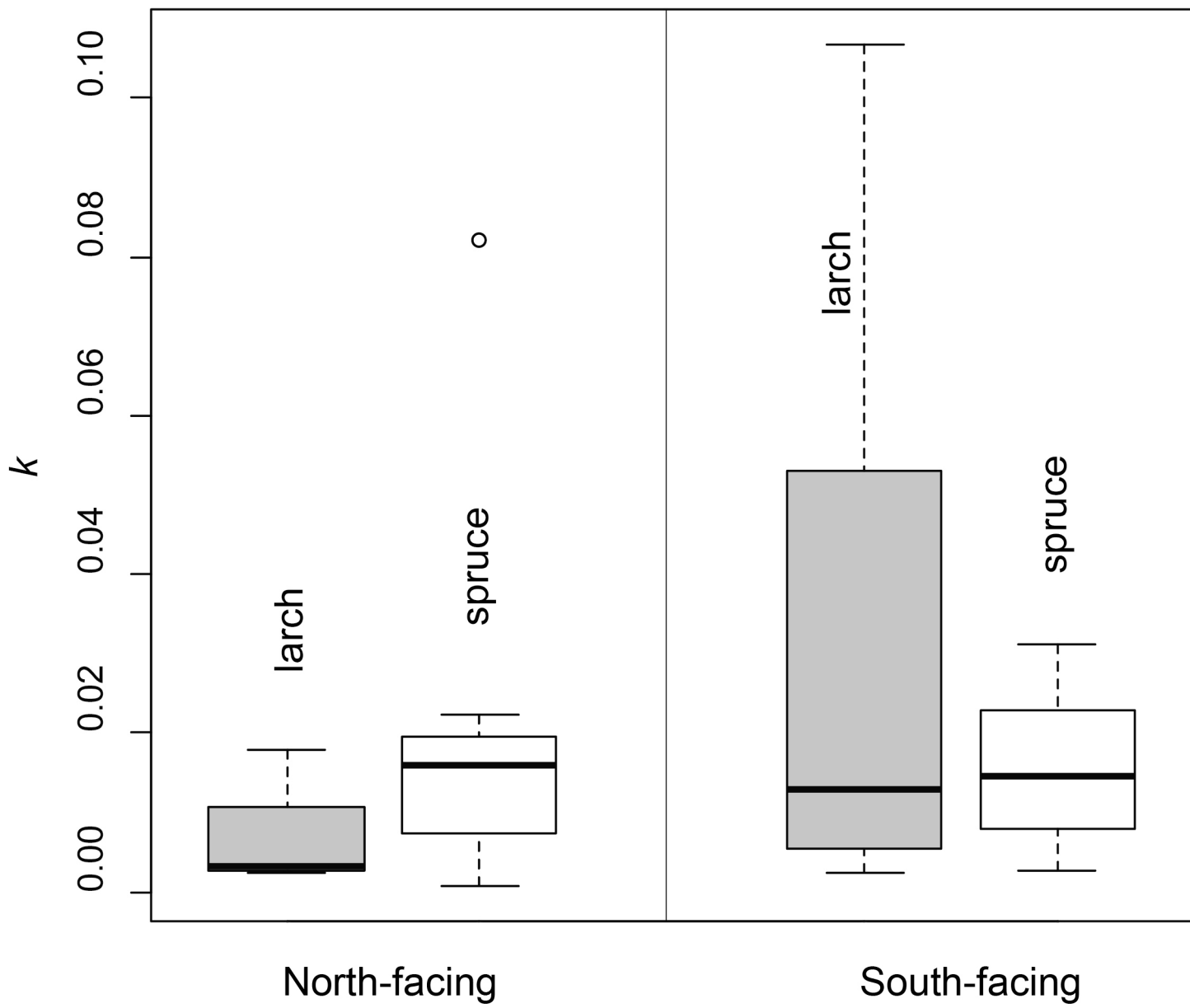


Fig. 5



**Fig. 6**



# Fig. 7

